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ODA PILOT STUDY II: SELECTION OF AN INTERACTIVE GRAPHICS CONTROL DEVICE FOR CONTINUOUS SUBJECTIVE FUNCTIONS APPLICATIONS

REPORT NO. 215-2

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OFFICE OF NAVAL RESEARCH
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THIS REPORT PRESENTS THE RESULTS OF A PILOT STUDY UNDERTAKEN TO EVALUATE THE PERFORMANCE OF THREE INTERACTIVE GRAPHICS CONTROL DEVICES--LIGHT PEN, TRACK BALL, AND JOY STICK--FOR THE TYPES OF "DRAWING" TASKS REQUIRED TO DETERMINE CONTINUOUS SUBJECTIVE FUNCTIONS (CSF'S). THIS REPORT INCLUDES (1) A BRIEF REVIEW OF CSF'S IN THE CONTEXT OF COMPUTER-AIDED DECISION MAKING; (2) A DESCRIPTION OF THE TYPES OF DRAWING TASKS USED IN GENERATING CSF'S; AND (3) THE EXPERIMENTAL DESIGN, PROCEDURES, PERFORMANCE MEASURES, AND INTERPRETATION

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20. ABSTRACT (CONTINUED)

OF RESULTS. THE RESULTS OF THIS STUDY CONCLUDE THAT THE TRACK BALL IS THE BEST OVERALL CONTROL DEVICE FOR USE IN SUBSEQUENT CSF STUDIES.

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1.0 INTRODUCTION

As part of the Operational Decision Aids (ODA) program, Integrated Sciences Corporation is conducting experimental investigations of man-machine interface (MMI) concepts. The current task is directed toward the development and evaluation of Continuous Subjective Functions (CSF) as they apply to computer-aided decision making. The use of Continuous Subjective Functions is one means by which a decision maker (e.g., Task Force Commander (TFC)) can convey his estimate of a given situation to the decision aiding hardware. As such, it can represent an alternative to less comprehensive methods, such as eliciting scalar estimates for man-to-machine transfer of subjective judgments.

One way to implement a CSF via decision aiding equipment is for the decision maker to "draw" the curve, line, or surface representing his estimate on a computer-driven graphics display. Various types of control hardware are available to perform drawing tasks in conjunction with an interactive graphics display; among them are the light pen, the track ball, and the joy stick. The light pen is one of the most commonly used devices; it consists of a hand-held fiber-optic tube that can be "pointed" at a light source (e.g., cursor) on the screen and used to move the cursor to produce a line. The joy stick and track ball are both analog devices. The joy stick resembles a pilot's control stick; the track ball consists of a recess-mounted sphere that can be rotated by the palm of the hand. Both are equipped with potentiometers, the signals of which are converted to digital x- and y-values, so that the cursor on the screen moves in direct proportion to the movement of the device.

This pilot study was undertaken to evaluate the light pen, track ball, and joy stick in relation to types of drawing tasks to be performed in subsequent CSF research. By determining in advance which of the three control devices yields the best performance in CSF-type tasks helps to avoid confounding the main experiment. Accordingly, the primary experimental null

hypothesis was that there is no significant difference among devices. This report documents the results of the three-factor analysis of variance, describes the results of tests on observed differences among devices, and develops a criterion function that aids the selection of the best device.

2.0 EXPERIMENTAL DESIGN

2.1 OPERATOR TASKS

The generation of a Continuous Subjective Function (CSF) may require a variety of "drawing" tasks from the operator. Thus the graphic representation of a subjective function may be accomplished by drawing straight line segments, curves, or surfaces, depending on the function. Furthermore, curves may either be continuous (e.g., circles) or discrete (e.g., histograms). In addition, a drawing task may be further classified into three categories:

- Sketching
- Tracing
- Pseudo-tracing

In this context, "sketching" refers to the transfer of a mental image to the graphics display screen without the aid of visual reference--or anchor--points. "Tracing" involves generating a visual image aided by a series of closely spaced anchor points; when done on a CRT, tracing is analogous to a "connect-the-dots" routine. "Pseudo-tracing" involves aspects of both sketching and tracing: there may be certain points, lines, or other data available as visual references, but they are not so many that the task becomes simply mechanical.

Since sketching and pseudo-tracing of straight lines and curves are the types of drawing tasks involved in the production of a CSF, the experiment included both types. The experimental tasks excluded (insofar as possible) a subject operator's artistic ability or mathematical sophistication as an influence on the results. Another factor influencing the selection of experimental tasks was the need for straightforward measurement of operator performance across control devices. Figure 1, for instance, shows two possible operator estimates (broken lines) of a CSF (solid line).

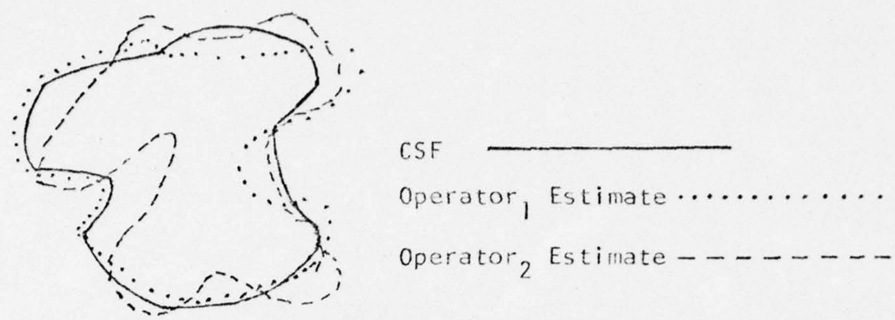

Figure 1. Example CSF Estimates.

To measure which operator estimate is a better rendition of the desired shape was considered needlessly complex for this experiment. Instead, one or two simple geometric figures were needed, which (1) required the types of drawing tasks desired, (2) were commonly understood, and (3) allowed direct measurement of deviations. Accordingly, two commonly known geometric figures were chosen for the drawing task: the equilateral triangle and the circle. Both figures readily yield commonly held and repeatable mental images; this helped to measure more directly performance due to the control devices. Selection of these two figures also allowed the definition of the dependent variables to be relatively straightforward (see Section 2.2).

Finally, drawing the two figures involved both sketching and pseudo-tracing tasks. Drawing the circle is defined as purely a sketching task: no visual anchor points were available to the subject operator. Drawing the equilateral triangle as a whole is taken to be a sketching task; but additional distinctions were made for generating the individual line segments of the triangle. These distinctions are as follows: first, the order and direction in which the sides of the triangle were to be drawn were specified, in order to simplify the sampling of points (done in software) on the line segments. These specifications are shown in Figure 2.

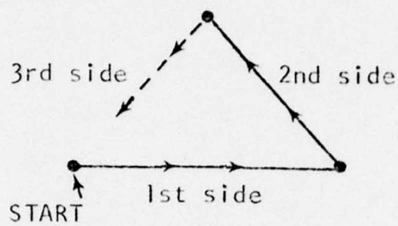

Figure 2. Triangle Sketching Procedure.

Drawing the first side was defined as a pseudo-sketching task; since the line was to be horizontal, the operator could take advantage of the edge of the screen as a reference. The second side required sketching: the operator had to judge the proper length and slope of the line without the benefit of easily used landmarks. Drawing the third side consisted of a pseudo-sketching task with anchor points, i.e., two vertices of the triangle; the operator had only to draw a straight line segment between the two points.

In summary, drawing the circle was a sketching task only, while drawing the triangle involved a transition from pseudo-tracing to sketching to pseudo-tracing with anchor points. These distinctions helped to define the experimental dependent variables which are the performance measures of the circle- and triangle-drawing tasks.

2.2 DEPENDENT VARIABLES

To evaluate performance of three control devices for these drawing tasks, nine performance variables were defined. Eight were recorded for each operator-drawn triangle and one for each circle. Thus, both straight and curved line sketching were measured, as well as straight line pseudo-tracing.

First, the straightness of each side of the triangle was measured. For each side, points were sampled from the drawn line according to a software-controlled time/distance criterion. Linear regression coefficients for a least-squares fit were calculated (Equations 1 and 2) from the x- and y-coordinates of the sampled points on the line:

$$a_1 = \frac{\Sigma x_i y_i - \frac{\Sigma x_i \Sigma y_i}{n}}{\Sigma x_i^2 - \frac{(\Sigma x_i)^2}{n}} \tag{1}$$

$$a_2 = \frac{\Sigma y_i}{n} - a_1 \frac{\Sigma x_i}{n} \tag{2}$$

where the summations over i go from 1 to n, the number of sampled points. Next, estimated values of y_i were computed for each value of x_i on the line according to the regression equation (3):

$$\hat{y}_i = a_1 x_i + a_2 \tag{3}$$

The residual is then defined to be:

$$R_i = (\hat{y}_i - y_i)^2 \tag{4}$$

where y_i equals the raw y-value of the sampled point on the drawn line.

Then for each of the three sides, the mean residual and standard deviation of the residuals were calculated according to Equations 5 and 6 respectively:

$$\bar{R}_i = \frac{\Sigma R_i}{n-2} \tag{5}$$

$$\sigma_{R_i} = \frac{\sqrt{\Sigma R_i^2 - (\Sigma R_i)^2/n}}{(n-1)} \tag{6}$$

To measure how closely the triangle drawn on the screen resembled an equilateral triangle. standard deviations for the length of the sides and for the size of the angles were computed. The lengths, L_i, of the three sides were calculated according to the Euclidian distance between the

respective vertices. Mean length, $\bar{L}$, was computed; the standard deviation for the lengths was obtained by:

$$\sigma_L = \frac{1}{\bar{L}} \sqrt{\frac{\Sigma L_i^{\,2} - 3(\bar{L})^2}{2}} \qquad (7)$$

The angles, α_i, were determined (again from the vertices of the triangle) and the standard deviation, σ_α, was computed by:

$$\sigma_\alpha = \sqrt{\frac{\Sigma\alpha_i^{\,2} - 3(60)^2}{2}} \qquad (8)$$

The single performance variable recorded for the circle was the standard deviation of distance (radius), r_i, from the centroid of the sampled points of the drawn figure. The centroid (x_c, y_c) was taken to be the mean of the x- and y-coordinates of the sampled points. Distance from the centroid to each sampled point was determined by the Euclidian distance formula, so that the standard deviation was given by:

$$\sigma_r = \frac{1}{\bar{r}} \sqrt{\frac{\Sigma r_i^{\,2} - n(\bar{r})^2}{n-1}} \qquad (9)$$

To summarize, nine performance measures were recorded for each trial:

(1-3) Three values of σ_{R_i}, the standard deviation of residuals for each side of the triangle.

(4-6) Three values of $\bar{R}_i$, the mean residuals for each side of the triangle.

(7) One value of σ_L, the standard deviation of the lengths of the sides of the triangle.

(8) One value of σ_α, the standard deviation of the angles of the triangles.

(9) One value of σ_r, the standard deviation of the radii of the circle.

2.3 INDEPENDENT VARIABLES

The three independent variables for the experiment were:

(1) Subject operators

(2) Interactive graphics control devices

(3) Replications

Five subject operators were used. All were U.C.L.A. undergraduates in the fields of engineering, computer science, and psychology. Three control devices were used: joystick, trackball, and lightpen. Four complete replications were performed; each replication consisted of four triangles and four circles drawn per each control device per subject.

2.4 ANOVA DESIGN

The effects of possible differences in devices, operators, and replications on performance were of interest. Therefore it was decided to conduct a three factor, fully replicated, randomized block factorial experiment to determine if there were significant performance differences due to the factors or their interactions. There were three devices, five operators, and four replications. Each replication on a performance measure consisted of four data points generated by an operator during a single session. Thus, the data matrix for a single performance measure and one replication has the structure of Table 1. The full data matrix for a performance is 3 devices $\times$ 5 operators $\times$ 4 replications $\times$ 4 data points per replication. The model is:

$$Y_{ijkm} = U + R_i + D_j + RD_{ij} + O_k + RO_{ik} + OD_{jk} + RDO_{ijk} + \varepsilon_{m(ijk)} \quad (10)$$

The levels of devices are clearly fixed and not chosen at random. Operators were not chosen at random from any population of potential users of the control devices in a military setting. Therefore the results of

Table 1. ANOVA Data Matrix

	Performance Measure														
Device	JOYSTICK					TRACKBALL					LIGHTPEN				
Operator	01	02	03	04	05	01	02	03	04	05	01	02	03	04	05
	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Replication_i	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

the experiment are not generalizable to any population and "operators" must be considered a fixed variable. Replications are assumed to be a random variable. Since there are two factors at fixed levels and one at random levels, the model is a mixed effects model.

3.0 EXPERIMENTAL PROCEDURE

3.1 SINGLE TRIAL PROCEDURE

Each experimental session was conducted by a test director and two subject operators. For each trial, the test director selected the control device to be used for that trial; a single trial consisted of drawing one triangle and one circle with the selected control device.

At the beginning of a session, the test director scheduled, via the teletype, the software package for the experiment. Responding to an interactive query at the teletype, the test director entered the identification number assigned to whichever subject operator was executing the trial. The test director then entered a number designating the control device to be used for that trial. The test director randomized his selection of control devices to minimize any sequential effects across devices. In general a subject operator did not use the same control device for two consecutive trials.

Once the program was scheduled and a control device selected, the subject operator--seated at the display console--began the trial. On the screen appeared a frame marking the boundaries of the screen area where the figures were to be drawn, and the legend "Position Cursor." The subject operator used the designated control device to move the cursor to the screen position he chose as the starting point for the first leg of the equilateral triangle. Once he had the cursor positioned at the chosen point, the operator depressed the lit function button, thus (1) marking the coordinates of the start point for the first line segment, and (2) freeing the control device to "draw" the first leg of the triangle. At the end of the first leg, the operator depressed the function button again to mark the coordinates of the second vertex of the triangle. The second leg was drawn, and the function button depressed to mark the starting point (vertex) of the third leg. The operator drew the final leg; when this third line segment was within a software-specified distance of the initial start point

for the triangle, the figure was automatically closed. For sampling purposes, each side of the triangle had to be at least two inches long; if the completed operator-drawn figure did not satisfy this requirement, a message appeared on the display screen instructing the operator to redraw the figure. In this case the operator repositioned the cursor and proceeded as before.

If the triangle met the specifications, the operator next proceeded to draw the circle. Using the same control device designated at the start of the trial, he positioned the cursor at the desired start point, again within the frame appearing on the display. To draw the figure, the operator depressed the single, lit function button and proceeded to use the control device to produce the circle. In this case, there was no requirement for direction in which the circle was drawn: the operator was free to proceed either clockwise or counterclockwise. Again, the figure was closed automatically when the cursor was within the prespecified distance of the initial point. If the completed circle was less than the specified one-inch radius, the operator was instructed--via a message on the display--to redraw the figure. If the circle satisfied this requirement, the trial was over, and the test director defined the next trial by selecting another of the control devices and/or the other member of the subject operator team.

3.2 SCHEDULE

Prior to the experimental sessions performed for data collection, the subject operators participated in a series of training sessions undertaken to familiarize the subjects with the hardware and experimental procedures and to help minimize learning effects during the data collection phase. The training sessions were also used to identify and discourage any operating strategies developed by a subject that could affect the experimental results. The test director was on hand to educate the subjects in the use of the hardware, monitor practice runs, and provide training feedback.

Data gathering sessions were initiated once the subjects were familiar with equipment and procedures. A single session consisted of the test director and two subject operators and was scheduled for two hours. The subjects performed trials according to the sequence dictated by the test director. Since the individual trials could be completed fairly quickly, each subject was able to complete one replication per session; any time remaining in the two-hour session was devoted to training tasks pertaining to the main experiment (in progress).

4.0 DISCUSSION OF RESULTS

4.1 TESTS OF SIGNIFICANCE

Tests of significance were performed for each main effect and for the first- and second-order interactions. Computed values of the F ratios for each performance measure are given in Appendix A; levels of significance are shown in Table 2.

Several preliminary conclusions were indicated by the results shown in Table 2. First, devices were clearly significant for all performance measures involving straight- or curved-line drawing tasks. Second, replications appeared to be significant. This was discounted however, because the Replication x Device interaction was not significant, i.e., there were no significant learning or boredom effects that selectively affected devices. Third, operators appeared to be significant in tasks involving straight lines. In this case, the results could not be overlooked since Device x Operator interaction was also significant for six of the eight performance measures involving straight line drawing.

The Device x Operator interactions were plotted for the significant performance measures (Figures 3-8). Examination of the interactions for performance measures on the second leg of the triangle (Figures 3 and 4) shows drastic differences among operators for both the joy stick and light pen. These interactions also show that the common element across all operators is that the track ball yields the best (or insignificantly different from the best) performance. Figures 5 and 6, showing the interaction for performance measures on the third leg of the triangle, are less clear cut. It appears that the results are highly individualized by subject operators. Clearly, operators 2 and 3 differ markedly in performance from the other members of the experimental group. (In a real world situation, these two might be assigned to more appropriate jobs.) Otherwise, among operators 1, 4, and 5, the track ball again seems to yield the best (or insignificantly different from the best) performance. Figures

Table 2. Results of ANOVA Significance Tests.

Performance Measure / Source	Triangle Segment Straightness						Triangle Regularity		Circularity
	σ_{R_1}	σ_{R_2}	σ_{R_3}	$\bar{R}_1$	$\bar{R}_2$	$\bar{R}_3$	σ_L	σ_α	σ_r
Replications (R)	--	.01	.01	--	.05	.001	--	--	--
Devices (D)	.001	.01	.01	.001	.01	.05	--	--	.01
R x D	--	--	--	--	--	--	--	--	--
Operators (O)	--	.01	.005	.05	.005	.001	.01	.01	--
R x O	--	.01	.01	--	--	.001	.001	.001	--
D x O	--	.01	.01	--	.001	.05	.001	.001	--
R x D x O	--	.05	--	--	--	--	--	--	--

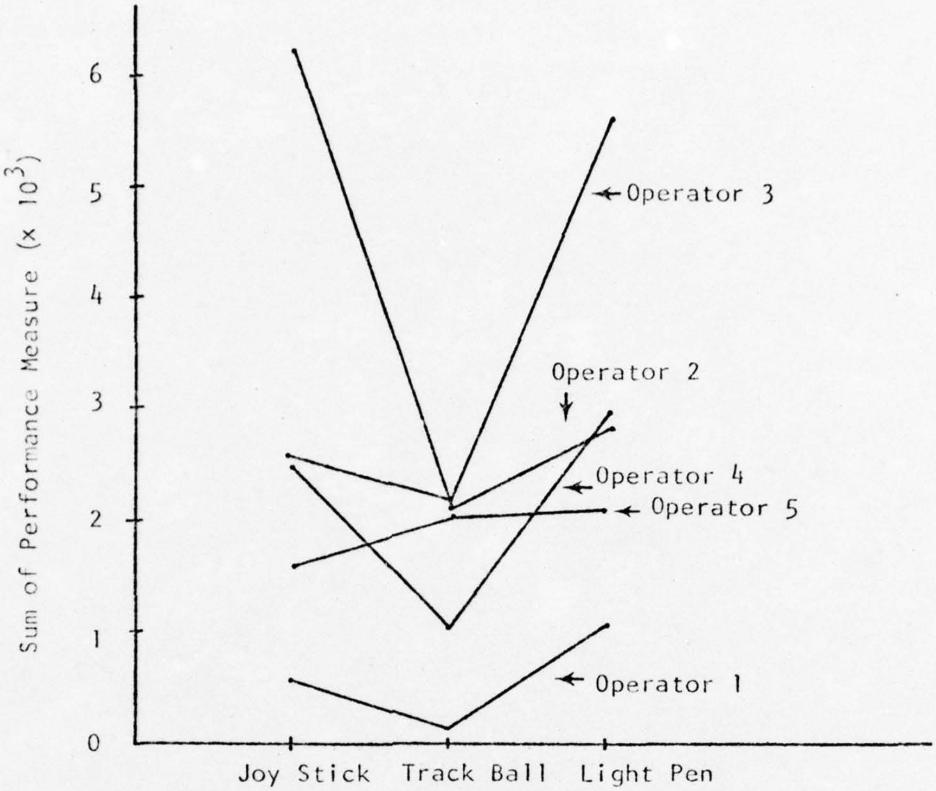

Figure 3. Device x Operator Interaction for Standard Deviation of Residuals, Triangle Side Two (σ_{R_2}).

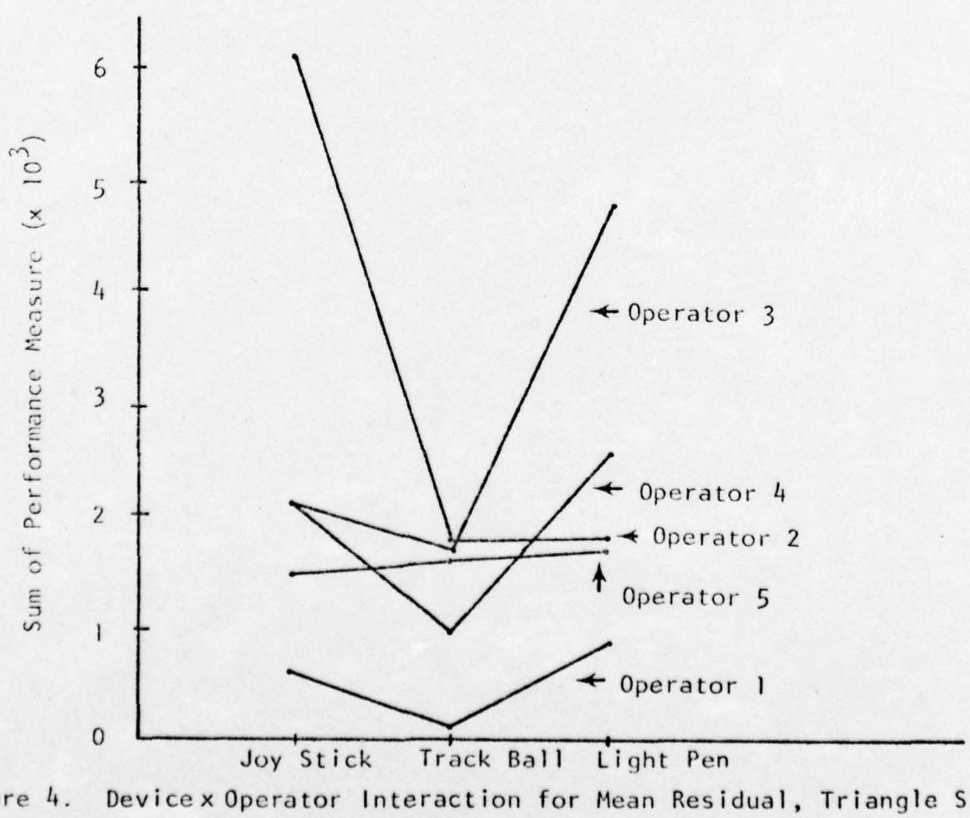

Figure 4. Device x Operator Interaction for Mean Residual, Triangle Side 2($\bar{R}_2$).

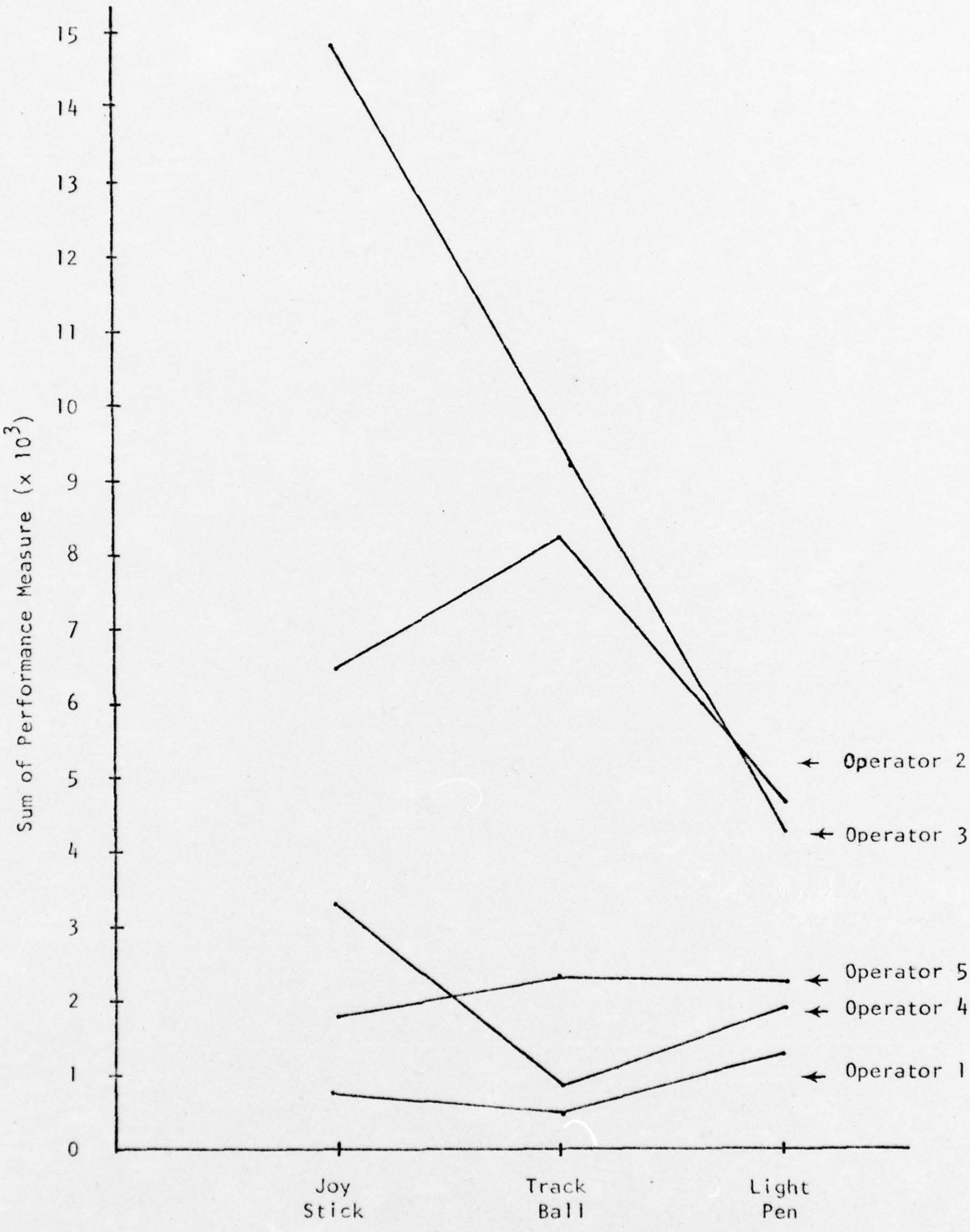

Figure 5. Device × Operator Interaction for Standard Deviation of Residuals, Triangle Side Three (σ_{R_3}).

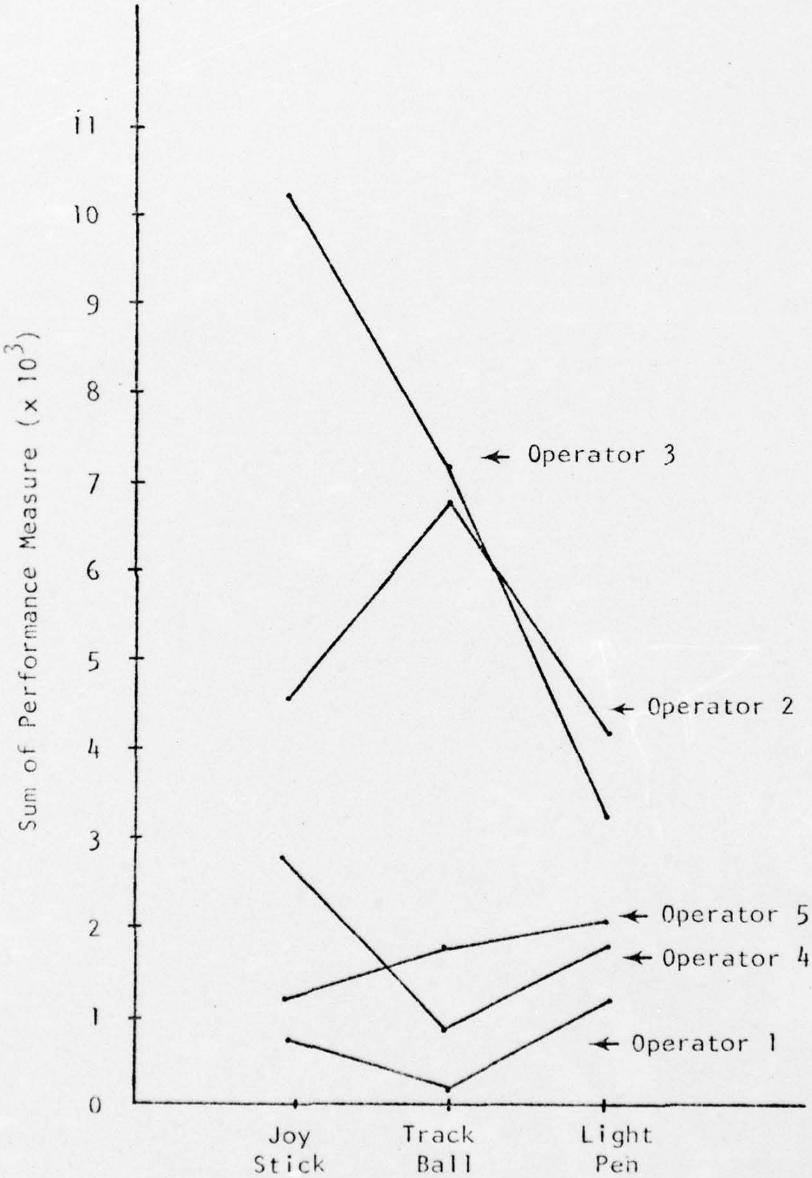

Figure 6. Device x Operator Interaction for Mean Residual, Triangle Side 3 ($\bar{R}_3$)

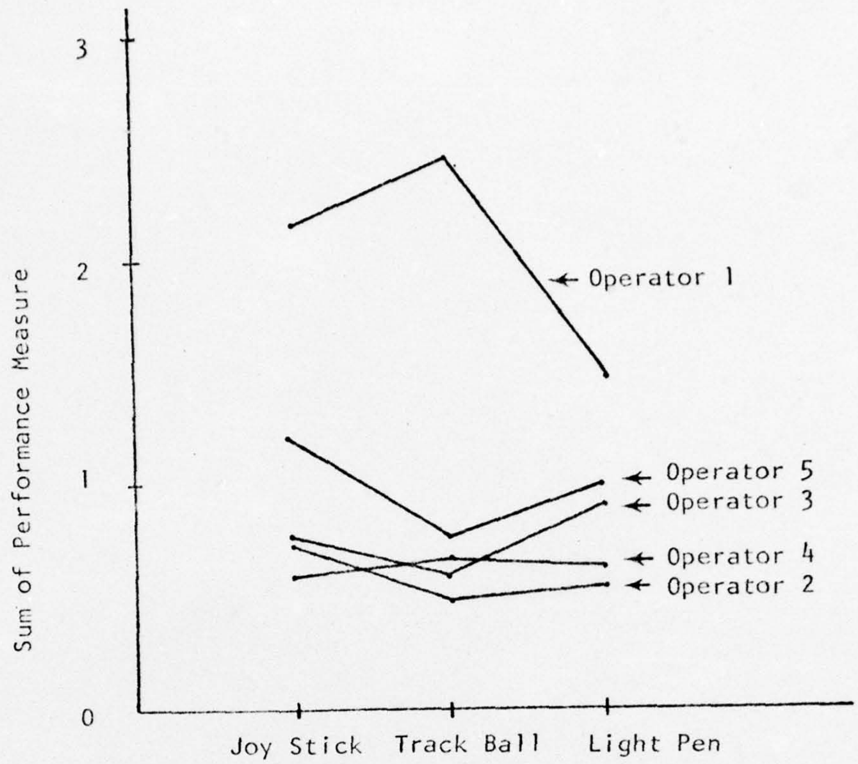

Figure 7. Device x Operator Interaction for Standard Deviation of Triangle Segment Lengths (σ_L).

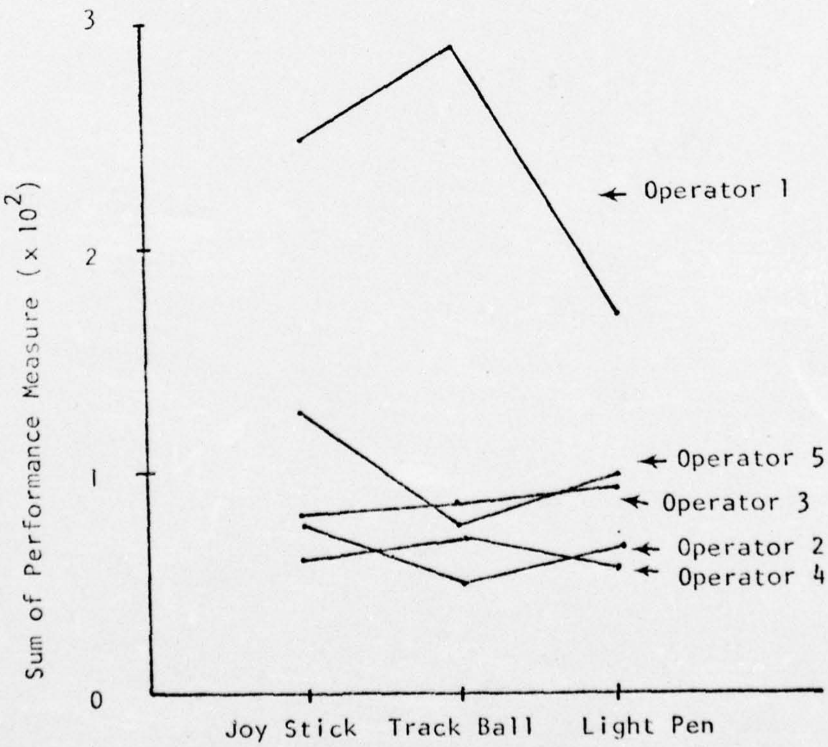

Figure 8. Device x Operator Interaction for Standard Deviation of Angles (σ_α).

7 and 8, for measures of the regularity of the triangle (σ_L and α) show that--except for one operator--there appears to be little difference among the devices. This might be expected because devices alone were not significantly different for these performance measures (Table 2) and because producing an equilateral triangle can be expected to depend more on an operator's spatial judgement than on the control device used.

4.2 RANK OF DEVICES

Since control devices were significant for straight and curved line drawing tasks, the total means for devices were ranked numerically and the contrasts among devices tested by Scheffé's method to provide a preliminary indication of which device was best. Results are shown in Table 3. From the table, it can be seen that on the basis of observed differences among the devices, the track ball was most often the superior device. In conjunction with the results of Scheffé's test, the track ball appears to be the best device for straight-line tracing (σ_{R_1} and $\overline{R}_1$) and is clearly the best for straight-line sketching (σ_{R_2} and $\overline{R}_2$). Judging from observed differences only, the light pen yielded the best performance for straight-line pseudo-tracing with anchor points (σ_{R_3} and $\overline{R}_3$). Tests on the means of these measures, however, were inconclusive. In the first case (σ_{R_3}), the contrast between the light pen and joy stick is significant, but the track ball is not significantly different from either. In the second case ($\overline{R}_3$) no mean is significantly different from any other mean. For these two performance measures, then, it is difficult to judge between the track ball and light pen as to which is the better device for this pseudo-tracing task. For the performance measure (σ_r) for curved-line sketching, Scheffé's test did not support the observed numerical superiority of the track ball. In this case, as for $\overline{R}_3$, none of the means was significantly different from any other mean.

Scheffé's test is, of course, less sensitive to observed differences than are other tests on means, hence one possible source of inconclusive

Table 3. Numerical Rank of Devices and Results of Scheffé's Test.

Performance Measure		Numerical Rank			Scheffé's Test		
		Joy Stick	Track Ball	Light Pen	Joy Stick	Track Ball	Light Pen
Standard Deviations of Residuals	σ_{R_1}	2	1	3	1	1	2
	σ_{R_2}	2	1	3	2	1	2
	σ_{R_3}	3	2	1	Test Inconclusive		
Mean Residuals	$\bar{R}_1$	2	1	3	1	1	2
	$\bar{R}_2$	3	1	2	2	1	2
	$\bar{R}_3$	3	2	1	Test Inconclusive		
Standard Deviation of radii	σ_r	3	1	2	Test Inconclusive		

results for three of the performance measures. The information displayed in Table 3, however, suggests that the track ball is a reasonable choice among the devices for both straight- and curved-line drawing tasks. The track ball is clearly best for straight-line sketching and also displays the best performance value (lowest total mean) for curved-line sketching (σ_r).

4.3 CRITERION FUNCTION EVALUATION

A second evaluation of the control devices was carried out by means of a normalized, weighted, linear sum criterion function. The first step in formulating the criterion function was to simplify the evaluation by eliminating irrelevant or redundant performance measures from consideration. Therefore, σ_L and σ_α (measures of regularity of the triangle) were eliminated because devices were not significantly different for these variables (Table 2). In addition, the three standard deviations of residuals of the sides of the triangles (σ_{R_1}, σ_{R_2}, σ_{R_3}) were eliminated because--for purposes of the criterion function--they were considered redundant with the three mean residuals of the sides of the triangle ($\overline{R}_1$, $\overline{R}_2$, and $\overline{R}_3$). Of the four remaining performance measures of interest, three were measures of straight-line drawing tasks and one was a measure of curved-line drawing. They are:

(1) $\overline{R}_1$: a measure of straight-line pseudo-tracing with a reference frame

(2) $\overline{R}_2$: a measure of straight-line sketching

(3) $\overline{R}_3$: a measure of straight-line pseudo-tracing with anchor points

(4) σ_r : a measure of curved-line sketching.

The functional form of the criterion function is given by Equation 11:

$$CF_i = \sum_{j=1}^{4} w_j \frac{PM_{ij}}{PM_j^*} \tag{11}$$

where:

CF_i = criterion function value of the i^{th} device

w_j = the weighting coefficient of the j^{th} performance measure

PM_{ij} = the experimental value of the performance measure of the i^{th} device on the j^{th} performance measure (total mean experimental value)

PM_j^* = the value of the best (minimum) performance measure among the three devices for the j^{th} performance measure

and:

$$\sum_{j=1}^{4} w_j = 1.0 \qquad (12)$$

Since three of the performance measures pertained to straight-line drawing tasks, it was decided to use w_{σ_r} as the sensitivity variable, so that from (12):

$$w_{\overline{R}_1} + w_{\overline{R}_2} + w_{\overline{R}_3} = 1 - w_{\sigma_r} \qquad (13)$$

The order of importance of the types of straight-line drawing tasks was defined and subjective ratio factors assigned. Since sketching was considered most consistent with CSF-type tasks, $\overline{R}_2$ was assigned the rank of one; $\overline{R}_1$ and $\overline{R}_3$ were ranked two and three, respectively. The relative importance of the straight-line drawing tasks is expressed in Equations (14) and (15) by subjective constant ratio constraints.

$$\frac{w_{\overline{R}_1}}{w_{\overline{R}_2}} = \frac{.20}{.25} \qquad (14)$$

$$\frac{w_{\overline{R}_2}}{w_{\overline{R}_3}} = \frac{.25}{.15} \qquad (15)$$

The sensitivity analysis consisted of selecting a value for the sensitivity variable, w_{σ_r}; solving the system of equations (13, 14, and 15) for $w_{\bar{R}_1}$, $w_{\bar{R}_2}$, and $w_{\bar{R}_3}$; and using these solved values of w_i to compute the value of CF_i (Equation 11).

The results are plotted in Figure 9 for values of interest of the sensitivity variable, namely from 0.4 to 0.8. The plot indicates that the track ball and joy stick are markedly consistent across performance measures, i.e., their respective performances are quite similar for the types of drawing tasks (straight vs. curved lines) examined here. The slope of the plot for the light pen suggests that the light pen's performance varies among the drawing tasks, with a relative superiority for curved line sketching. The primary interpretation of the criterion function evaluation, however, is that the track ball appears to be always the best device regardless of the subjective weighting of the curved ($w(\sigma_r)$) line sketching performance factor.

4.4 CONCLUSIONS

The analysis of variance indicated that the three interactive graphics control devices examined in this study were significantly different for a range of drawing tasks--especially straight- and curved-line sketching of the type used to represent continuous subjective functions. Although the results of using Scheffé's test did not show the track ball to be superior in all cases, they provide a reasonable basis for selecting the track ball as the preferred device. On the basis of the criterion function evaluation, the track ball is clearly the best device overall. The combined impact of these results, therefore, indicates that the track ball will be the single control device of choice for all subsequent continuous subjective function applications.

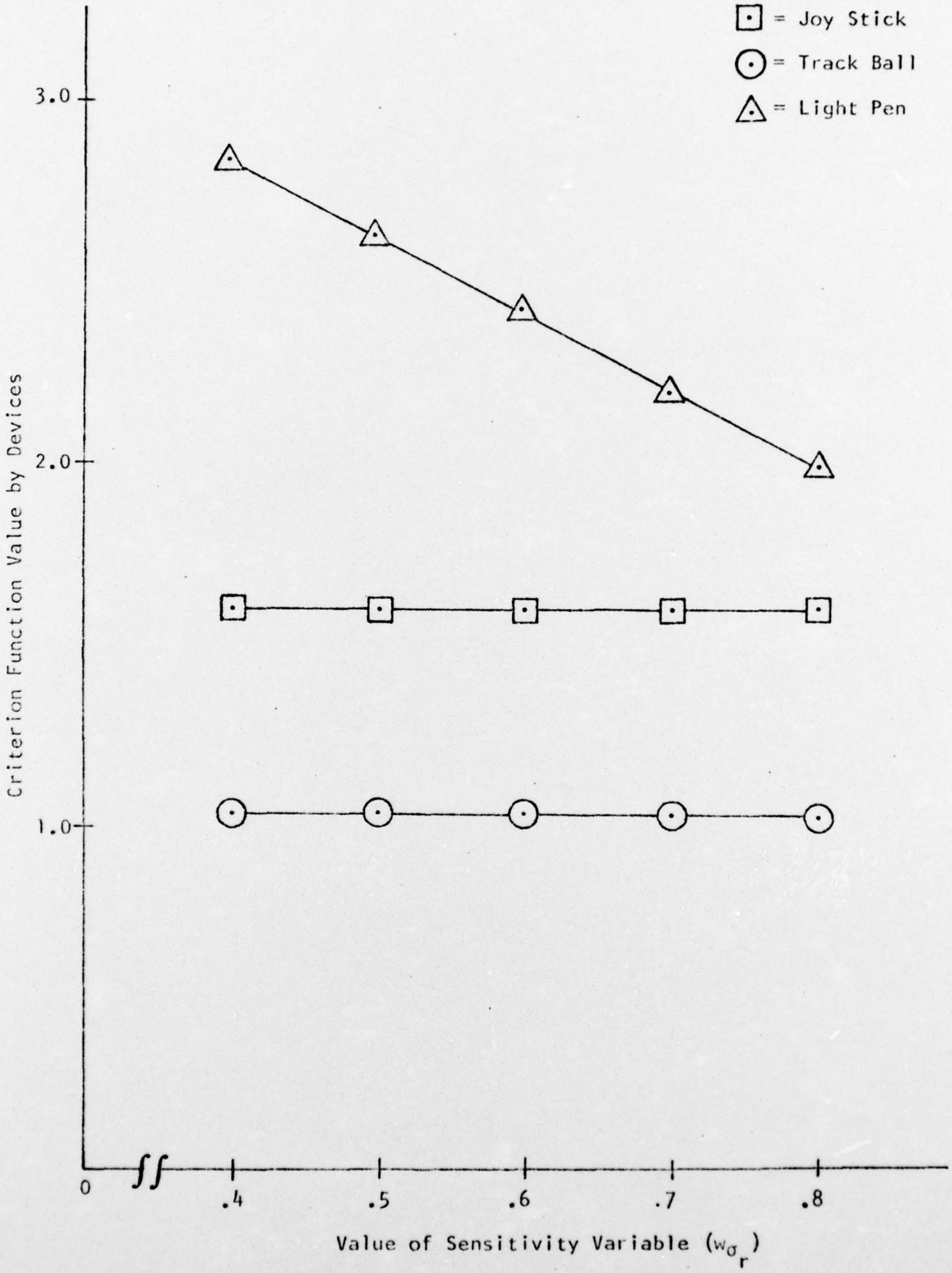

Figure 9. Results of Criterion Function Analysis.

APPENDIX A

ANOVA TABLES

Table 4 . ANOVA Table: Standard Deviation of Residuals (σ_{R_1}), Side 1.

Source	Degrees of Freedom	Sum of Squares	Mean Square	Error Mean Square	F
R_i	3	$.1325 \times 10^4$	4.417×10^2	$\sigma_\varepsilon^2 + 15\sigma_R^2$	0.5791
D_j	2	$.5200 \times 10^5$	2.600×10^4	$\sigma_\varepsilon^2 + 20\sigma_D^2 + 5\sigma_{RD}^2$	39.66
RD_{ij}	6	$.3933 \times 10^4$	6.555×10^2	$\sigma_\varepsilon^2 + 5\sigma_{RD}^2$	0.8593
O_k	4	$.6122 \times 10^4$	1.531×10^3	$\sigma_\varepsilon^2 + 12\sigma_O^2 + 3\sigma_{RO}^2$	2.466
RO_{ik}	12	$.7451 \times 10^4$	6.209×10^2	$\sigma_\varepsilon^2 + 3\sigma_{RO}^2$	0.8140
OD_{jk}	8	$.4394 \times 10^4$	5.493×10^2	$\sigma_\varepsilon^2 + 4\sigma_{OD}^2 + \sigma_{RDO}^2$	0.8073
RDO_{ijk}	24	$.1633 \times 10^5$	6.804×10^2	$\sigma_\varepsilon^2 + \sigma_{RDO}^2$	0.8920
$\varepsilon_{m(ijk)}$	180	$.1373 \times 10^6$	7.628×10^2	σ_ε^2	Not Applicable
TOTAL	239	$.2288 \times 10^6$			

Table 5. ANOVA Table: Standard Deviation of Residuals (σ_{R_2}), Side 2.

Source	Degrees of Freedom	Sum of Squares	Mean Square	Error Mean Square	F
R_i	3	$.2875 \times 10^6$	9.583×10^4	$\sigma_\varepsilon^2 + 15\sigma_R^2$	4.668
D_j	2	$.3267 \times 10^6$	1.634×10^5	$\sigma_\varepsilon^2 + 20\sigma_D^2 + 5\sigma_{RD}^2$	10.94
RD_{ij}	6	$.8962 \times 10^5$	1.494×10^4	$\sigma_\varepsilon^2 + 5\sigma_{RD}^2$	0.7277
O_k	4	$.1286 \times 10^7$	3.215×10^5	$\sigma_\varepsilon^2 + 12\sigma_O^2 + 3\sigma_{RO}^2$	6.233
RO_{ik}	12	$.6190 \times 10^6$	5.158×10^4	$\sigma_\varepsilon^2 + 3\sigma_{RO}^2$	2.512
OD_{jk}	8	$.8600 \times 10^6$	1.075×10^5	$\sigma_\varepsilon^2 + 4\sigma_{OD}^2 + \sigma_{RDO}^2$	3.304
RDO_{ijk}	24	$.7809 \times 10^6$	3.254×10^4	$\sigma_\varepsilon^2 + \sigma_{RDO}^2$	1.585
$\varepsilon_{m(ijk)}$	180	$.3696 \times 10^7$	2.053×10^4	σ_ε^2	Not Applicable
TOTAL	239	$.7946 \times 10^7$			

Table 6. ANOVA Table: Standard Deviation of Residuals (σ_{R_3}), Side 3.

Source	Degrees of Freedom	Sum of Squares	Mean Square	Error Mean Square	F
R_i	3	$.1451 \times 10^7$	4.837×10^5	$\sigma_\varepsilon^2 + 15\sigma_R^2$	6.170
D_j	2	$.9988 \times 10^6$	4.994×10^5	$\sigma_\varepsilon^2 + 20\sigma_D^2 + 5\sigma_{RD}^2$	12.15
RD_{ij}	6	$.2446 \times 10^6$	4.110×10^4	$\sigma_\varepsilon^2 + 5\sigma_{RD}^2$	0.5243
O_k	4	$.1024 \times 10^8$	2.560×10^6	$\sigma_\varepsilon^2 + 12\sigma_O^2 + 3\sigma_{RO}^2$	9.101
RO_{ik}	12	$.3375 \times 10^7$	2.813×10^5	$\sigma_\varepsilon^2 + 3\sigma_{RO}^2$	3.588
OD_{jk}	8	$.3119 \times 10^7$	3.899×10^5	$\sigma_\varepsilon^2 + 4\sigma_{OD}^2 + \sigma_{RDO}^2$	3.441
RDO_{ijk}	24	$.2720 \times 10^7$	1.133×10^5	$\sigma_\varepsilon^2 + \sigma_{RDO}^2$	1.445
$\varepsilon_{m(ijk)}$	180	$.1411 \times 10^8$	7.839×10^4	σ_ε^2	Not Applicable
TOTAL	239	$.3626 \times 10^8$			

Table 7. ANOVA Table: Mean Residual ($\bar{R}_1$), Side 1.

Source	Degrees of Freedom	Sum of Squares	Mean Square	Error Mean Square	F
R_i	3	$.1804 \times 10^3$	6.013×10^1	$\sigma_\varepsilon^2 + 15\sigma_R^2$	0.2720
D_j	2	$.3041 \times 10^5$	1.521×10^4	$\sigma_\varepsilon^2 + 20\sigma_D^2 + 5\sigma_{RD}^2$	98.77
RD_{ij}	6	$.9240 \times 10^3$	1.540×10^2	$\sigma_\varepsilon^2 + 5\sigma_{RD}^2$	0.6965
O_k	4	$.3555 \times 10^4$	8.888×10^2	$\sigma_\varepsilon^2 + 12\sigma_O^2 + 3\sigma_{RO}^2$	3.287
RO_{ik}	12	$.3245 \times 10^4$	2.704×10^2	$\sigma_\varepsilon^2 + 3\sigma_{RO}^2$	1.223
OD_{jk}	8	$.2294 \times 10^4$	2.868×10^2	$\sigma_\varepsilon^2 + 4\sigma_{OD}^2 + \sigma_{RDO}^2$	1.083
RDO_{ijk}	24	$.6352 \times 10^4$	2.647×10^2	$\sigma_\varepsilon^2 + \sigma_{RDO}^2$	1.197
$\varepsilon_{m(ijk)}$	180	$.3979 \times 10^5$	2.211×10^2	σ_ε^2	Not Applicable
TOTAL	239	$.8676 \times 10^5$			

Table 8. ANOVA Table: Mean Residual ($\bar{R}_2$), Side 2.

Source	Degrees of Freedom	Sum of Squares	Mean Square	Error Mean Square	F
R_i	3	$.1564 \times 10^6$	5.213×10^4	$\sigma_\varepsilon^2 + 15\sigma_R^2$	2.747
D_j	2	$.2910 \times 10^6$	1.455×10^5	$\sigma_\varepsilon^2 + 20\sigma_D^2 + 5\sigma_{RD}^2$	6.160
RD_{ij}	6	$.1417 \times 10^6$	2.362×10^4	$\sigma_\varepsilon^2 + 5\sigma_{RD}^2$	1.244
O_k	4	$.8841 \times 10^6$	2.210×10^5	$\sigma_\varepsilon^2 + 12\sigma_O^2 + 3\sigma_{RO}^2$	7.049
RO_{ik}	12	$.3762 \times 10^6$	3.135×10^4	$\sigma_\varepsilon^2 + 3\sigma_{RO}^2$	1.652
OD_{jk}	8	$.9335 \times 10^6$	1.167×10^5	$\sigma_\varepsilon^2 + 4\sigma_{OD}^2 + \sigma_{RDO}^2$	6.158
RDO_{ijk}	24	$.4547 \times 10^6$	1.895×10^4	$\sigma_\varepsilon^2 + \sigma_{RDO}^2$	0.9984
$\varepsilon_{m(ijk)}$	180	$.3416 \times 10^7$	1.898×10^4	σ_ε^2	Not Applicable
TOTAL	239	$.6653 \times 10^7$			

Table 9. ANOVA Table: Mean Residual ($\bar{R}_3$), Side 3.

Source	Degrees of Freedom	Sum of Squares	Mean Square	Error Mean Square	F
R_i	3	$.9051 \times 10^6$	3.017×10^5	$\sigma_\varepsilon^2 + 15\sigma_R^2$	6.687
D_j	2	$.2974 \times 10^6$	1.487×10^5	$\sigma_\varepsilon^2 + 20\sigma_D^2 + 5\sigma_{RD}^2$	8.051
RD_{ij}	6	$.1108 \times 10^6$	1.847×10^4	$\sigma_\varepsilon^2 + 5\sigma_{RD}^2$	0.4094
O_k	4	$.5322 \times 10^7$	1.331×10^6	$\sigma_\varepsilon^2 + 12\sigma_O^2 + 3\sigma_{RO}^2$	9.295
RO_{ik}	12	$.1718 \times 10^7$	1.432×10^5	$\sigma_\varepsilon^2 + 3\sigma_{RO}^2$	3.174
OD_{jk}	8	$.1596 \times 10^7$	1.995×10^5	$\sigma_\varepsilon^2 + 4\sigma_{OD}^2 + \sigma_{RDO}^2$	2.998
RDO_{ijk}	24	$.1597 \times 10^7$	6.654×10^4	$\sigma_\varepsilon^2 + \sigma_{RDO}^2$	1.475
$\varepsilon_{m(ijk)}$	180	$.8122 \times 10^7$	4.512×10^4	σ_ε^2	Not Applicable
TOTAL	239	$.1967 \times 10^8$			

Table 10. ANOVA Table: Standard Deviation (σ_L) for Lengths of Sides.

Source	Degrees of Freedom	Sum of Squares	Mean Square	Error Mean Square	F
R_i	3	$.4264 \times 10^{-2}$	1.421×10^{-3}	$\sigma_\varepsilon^2 + 15\sigma_R^2$	1.9247
D_j	2	$.4748 \times 10^{-2}$	2.374×10^{-3}	$\sigma_\varepsilon^2 + 20\sigma_D^2 + 5\sigma_{RD}^2$	1.911
RD_{ij}	6	$.7453 \times 10^{-2}$	1.242×10^{-3}	$\sigma_\varepsilon^2 + 5\sigma_{RD}^2$	1.682
O_k	4	.2711	6.778×10^{-2}	$\sigma_\varepsilon^2 + 12\sigma_O^2 + 3\sigma_{RO}^2$	5.972
RO_{ik}	12	.1362	1.135×10^{-2}	$\sigma_\varepsilon^2 + 3\sigma_{RO}^2$	15.37
OD_{jk}	8	$.3027 \times 10^{-1}$	3.784×10^{-3}	$\sigma_\varepsilon^2 + 4\sigma_{OD}^2 + \sigma_{RDO}^2$	5.428
RDO_{ijk}	24	$.1673 \times 10^{-1}$	6.971×10^{-4}	$\sigma_\varepsilon^2 + \sigma_{RDO}^2$	0.9442
$\varepsilon_{m(ijk)}$	180	.1329	7.383×10^{-4}	σ_ε^2	Not Applicable
TOTAL	239	.6036			

Table 11. ANOVA Table: Standard Deviation (σ_α) for Angles of Triangle.

Source	Degrees of Freedom	Sum of Squares	Mean Square	Error Mean Square	F
R_i	3	$.7133 \times 10^2$	2.378×10^1	$\sigma_\varepsilon^2 + 15\sigma_R^2$	2.103
D_j	2	$.7915 \times 10^2$	3.958×10^1	$\sigma_\varepsilon^2 + 20\sigma_D^2 + 5\sigma_{RD}^2$	1.923
RD_{ij}	6	$.1235 \times 10^3$	2.058×10^1	$\sigma_\varepsilon^2 + 5\sigma_{RD}^2$	1.820
O_k	4	$.3920 \times 10^4$	9.800×10^2	$\sigma_\varepsilon^2 + 12\sigma_O^2 + 3\sigma_{RO}^2$	5.704
RO_{ik}	12	$.2061 \times 10^4$	1.718×10^2	$\sigma_\varepsilon^2 + 3\sigma_{RO}^2$	15.19
OD_{jk}	8	$.5393 \times 10^3$	6.741×10^1	$\sigma_\varepsilon^2 + 4\sigma_{OD}^2 + \sigma_{RDO}^2$	6.488
RDO_{ijk}	24	$.2494 \times 10^3$	1.039×10^1	$\sigma_\varepsilon^2 + \sigma_{RDO}^2$	0.9187
$\varepsilon_{m(ijk)}$	180	$.2035 \times 10^4$	1.131×10^1	σ_ε^2	Not Applicable
TOTAL	239	$.9078 \times 10^4$			

Table 12. ANOVA Table: Standard Deviation (σ_r) of Distance from Centroid of Circle.

Source	Degrees of Freedom	Sum of Squares	Mean Square	Error Mean Square	F
R_i	3	$.6768 \times 10^{-2}$	2.256×10^{-3}	$\sigma_\varepsilon^2 + 15\sigma_R^2$	0.6475
D_j	2	$.3252 \times 10^{-1}$	1.626×10^{-2}	$\sigma_\varepsilon^2 + 20\sigma_D^2 + 5\sigma_{RD}^2$	11.20
RD_{ij}	6	$.8712 \times 10^{-2}$	1.452×10^{-3}	$\sigma_\varepsilon^2 + 5\sigma_{RD}^2$	0.4168
O_k	4	$.1660 \times 10^{-1}$	4.150×10^{-3}	$\sigma_\varepsilon^2 + 12\sigma_O^2 + 3\sigma_{RO}^2$	1.172
RO_{ik}	12	$.4250 \times 10^{-1}$	3.542×10^{-3}	$\sigma_\varepsilon^2 + 3\sigma_{RO}^2$	1.017
OD_{jk}	8	$.2555 \times 10^{-1}$	3.194×10^{-3}	$\sigma_\varepsilon^2 + 4\sigma_{OD}^2 + \sigma_{RDO}^2$	0.9469
RDO_{ijk}	24	$.8095 \times 10^{-1}$	3.373×10^{-3}	$\sigma_\varepsilon^2 + \sigma_{RDO}^2$	0.9681
$\varepsilon_{m(ijk)}$	180	.6272	3.484×10^{-3}	σ_ε^2	Not Applicable
TOTAL	239	.8408			